FIELD OF THE INVENTION

The present invention relates to a method allowing to determine a velocity model of seismic waves picked up by receivers coupled with an underground formation, from multi-offset records of these waves.

5   The methods allows easier access to the prestack kinematic information associated with the events contained in the seismic records, which is combined with a prestack kinematic inversion technique for imagery of the geologic interfaces of the subsoil.

What is referred to as "prestack kinematic information" is the traveltimes associated with the reflections recorded by source-pickup pairs located at variable distances from

10   one another. We contrast "easier access" with manual picking of the seismic events in the multi-offset collections. A "prestack kinematic inversion method" is understood to be a method allowing, from the kinematic information extracted from the seismic records (and not from an approximation of this kinematic information), to find the geometry of the associated reflectors and the layer velocities.

15   ## BACKGROUND OF THE INVENTION

Seismic reflection surveys are widely used in petroleum exploration, notably to produce images of the subsurface from the information contained in the waves propagated and reflected on the geologic discontinuities of the subsoil.

More precisely, imagery methods use the kinematic information associated with the

20   major seismic reflections (i.e. the traveltimes of the waves reflected on the main discontinuities of the subsoil) to determine a velocity macromodel of the subsoil, which will be used to convert the temporal seismic records to a depth image of the subsurface.

Access to the kinematic information necessary for determination of the velocity model requires interpretation of the seismic events in the seismic multi-offset records. Now, seismic multi-offset data is generally characterized by a bad signal-to-noise ratio, hence the failure of conventional automatic picking and the necessity of carrying out a

5   long and costly manual picking of the seismic data. Besides, for 3D seismic surveys (currently predominant in relation to 2D surveys), the quantity of data to be interpreted is a 4D volume that can reach sizes of the order of one hundred gigabytes, or even of the order of a terabyte, which makes the interpretative task even longer and tedious.

In order to avoid this stage of seismic multi-offset collection interpretation,

10   geophysicists have developed methods based on approximations of the geometry of the seismic events in the multi-offset collections. To establish these approximations, these methods put forward hypotheses on the subsoil complexity, hypotheses which can relate to the geometry of the geologic discontinuities of the subsoil and to the layer velocity variations. The method described by Taner and Kohler (1969) can for example be

15   mentioned, which assumes a stratified medium consisting of horizontal plane layers with homogeneous and isotropic layer velocities, as well as the method described by Levin (1971) which extends the previous method to sloping layers. Other variants have been proposed, but generally the existing methods are based on a hyperbolic hypothesis of the traveltime curve in the multi-offset collections. This hypothesis is however

20   violated from the moment that the geologic discontinuities of the subsoil are no longer plane and/or that the layer velocities exhibit lateral variations.

We propose here a method for best approaching the traveltimes of the multi-offset collections in cases where the geologic discontinuities of the subsoil have any geometry and where the layer velocities are moderately variable laterally, while limiting the

human time required for interpretation of the seismic records. The traveltimes obtained are then treated by means of a prestack kinematic inversion method allowing to take account of complex kinematics, such as traveltime tomography, described for example in the following document :

5   - Bishop, T. et al., 1985, "Tomographic Determination of Velocity and Depth in Laterally Varying Media", Geophysics, 50 No.6, 903-923.

The method can also apply in cases where the layer velocities are laterally variable, but iteratively, the velocity model after updating at a given iteration by applying a prestack kinematic inversion method such as the aforementioned reflection tomographic

10   method serving as the initial model for the next iteration.

SUMMARY OF THE INVENTION

The method according to the invention allows to determine a velocity model of seismic waves picked up by seismic receivers coupled with an underground formation, in response to the emission of seismic waves in the subsoil by a seismic source, after

15   reflection on geologic interfaces of said formation, from multi-offset records of these waves.

For each seismic event located on the records and for each layer delimited by said interfaces, the method comprises at least the following stages :

a) from the prestack seismic records, constructing an iso-offset collection from

20   which kinematic information or traveltimes associated with the event are extracted,

b) selecting a velocity range around a reference velocity in said layer, that is sampled with a predetermined interval,

c) for each velocity sample, applying an inversion technique at fixed velocity so as to determine, from the traveltimes extracted from the iso-offset collection, the geometry of said interface for the velocity sample concerned in order to obtain a series of interface/velocity pairs for said event,

5   d) calculating the kinematic information associated with each interface/velocity pair obtained, for source-receiver pairs corresponding to multi-offset collections existing in the seismic records,

e) for each interface/velocity pair and for each multi-offset collection selected, evaluating the coherence between the multi-offset traveltimes thus calculated and the seismic records, and selecting for each multi-offset collection the traveltime curve showing maximum coherence with the seismic records,

f) applying a prestack kinematic inversion method using the multi-offset traveltimes obtained for all the multi-offset collections selected, in order to determine the geometry and the velocity of the layer considered, and

15   g) iterating n times (n ≥ 0) stages a) to f) by considering on each iteration the velocity model obtained during the previous iteration as the reference model to define the reference velocity of the new iteration.

According to an implementation mode suitable in cases where the velocity range selected is not precise enough at the end of either the previous iteration or of stages a) to

20   f), stage g) is carried out n times with n ≥ 1.

According to another implementation mode suitable in cases where the velocities distribution varies greatly laterally and/or in cases where no sufficiently precise a priori

knowledge of the velocity distribution in the layer considered is available, stage g) is carried out on offset ranges that are increasingly wider as iterations progress.

According to another implementation mode suitable in cases where the velocities distribution varies greatly laterally and/or in cases where no sufficiently precise a priori

5   knowledge of the velocity distribution in the layer considered is available, stage g) is carried out on multi-offset collection grids that are increasingly finer as iterations progress.

According to an implementation mode suitable in cases where the sought interface geometry generates triplications, stage e) is carried out by considering the triplication

10   branches in the multi-offset collections independently of one another. Ray tracing and inversion tools allowing to take account of the multi-valued arrivals are used for example.

According to an implementation example, a zero-offset or a near-offset iso-offset collection is preferably constructed in stage a).

15   According to another implementation example, a fixed-velocity kinematic inversion technique such as a map migration is advantageously applied in stage c).

According to another implementation example, the kinematic information is calculated in stage d) by tracing multi-offset rays on the interface of each interface-velocity pair.

20   According to another implementation example, stage f) is advantageously carried out by applying a prestack kinematic inversion method such as a prestack traveltime tomography.

In its most general definition corresponding to the case where the number n of iterations to be carried out may possibly be zero, the method applies for example if the velocity distribution in each layer is hardly variable laterally and/or in the case where a sufficiently precise a priori on the velocity distribution in the layer considered is

5   available.

In its more restrictive definition where the number n of iterations to be carried out is at least 1, the method applies for example in the case where the velocity distribution in the layers of the geologic formation is greatly variable laterally and/or in the case where no sufficient a priori on the velocity distribution in the layer considered is available.

BRIEF DESCRIPTION OF THE FIGURES

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Other features and advantages of the method according to the invention will be clear from reading the description hereafter of non limitative embodiment examples, with reference to the accompanying drawings wherein :

- Figures 1a to 1c respectively show an application of the method to a common receiver

15   type multi-offset collection (Fig.1a), to a common receiver collection on which are superposed the multi-offset traveltimes obtained with various layer velocity values (Fig.1b) and to a common receiver collection on which is superposed the predicted multi-offset traveltime curve showing the greatest coherence with the seismic event considered (Fig.1c).

DETAILED DESCRIPTION

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We have seismic records obtained by means of a seismic device comprising a seismic source emitting seismic waves propagated in the subsoil, a set of seismic receivers coupled with the medium which pick up the waves reflected by the subsoil

discontinuities in response to the waves emitted, and of a laboratory for recording the seismic signals picked up.

I - Standard case

We present hereafter a first implementation mode of the method, in the case where

5   the velocities distribution in the geologic formation preceding the layer in question is known or has been estimated otherwise, the geometry of the layer in question generating no triplications, the velocity to be determined being hardly variable laterally or a sufficiently precise a priori on this velocity being available. The following stages are carried out :

10   I-1 From the prestack or multi-offset seismic records, constructing a collection of constant offset, preferably zero-offset (in reality an approximation of a zero-offset collection, known as stack, characterized by a better signal-to-noise ratio than the individual iso-offset sections) or near-offset (corresponding to the lowest offset of the multi-offset records).

15   If a coherent and sufficiently complete interpretation of the seismic event in progress can be carried out in this collection, picking is directly performed in this collection. In the opposite case, in order to gain access to the traveltimes associated with the event in question, a detour can be made via the time or depth migrated domain, followed by a time or depth demigration, as in the method described in :

20   - Ehinger, A., and Lailly, P., 1995, Velocity model determination by the SMART method, Part 1 : Theory : 65th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, pp.739-742.

I-2 A reference velocity is selected for the layer in question, as well as an uncertainty on this reference velocity and a sampling interval for the velocity range thus formed. We thus obtain a series of velocity samples for the layer in question; the reference velocity can be any velocity (i.e. laterally and vertically variable); in particular, if a velocity distribution obtained otherwise is available, this velocity can be used as the reference velocity; if no a priori information is available for the velocity of the layer, a laterally and vertically homogeneous reference velocity can be taken for example.

I-3 For each velocity sample, a fixed-velocity type kinematic inversion technique such as a map migration for example is applied in order to determine, from the traveltimes extracted from the constant-offset section, the geometry of said interface for the velocity sample in question; we thus obtain a series of interface/velocity pairs for the event in question. A description of map migration can for example be found in the following reference :

- Yilmaz, O., 2001, Seismic Data Analysis - Processing, Inversion and Interpretation of Seismic Data : Society of Exploration Geophysicists.

It may be impossible to find an interface model explaining the traveltimes for the fixed velocity in progress (impossibility of reaching convergence). For a higher efficiency of the method, it is possible to select only interface/velocity pairs for which the difference between the traveltimes observed and the traveltimes calculated on the model obtained after convergence is below a certain threshold.

It can be noted that this fixed-velocity inversion can also be carried out by means of any other equivalent kinematic technique.

I-4 The kinematic information associated with each interface/velocity pair obtained, for example by means of multi-offset ray tracing on the interface of each interface/velocity pair thus obtained and for source-receiver pairs corresponding to multi-offset collections existing in the seismic records is calculated. Common midpoint

5   collections are preferably used, in particular if the real velocity shows lateral variations that are not taken into account in the reference model.

I-5 For each interface/velocity pair and for each multi-offset collection selected, the coherence between the multi-offset traveltimes thus calculated and the seismic records is evaluated. A technique referred to as semblance calculation technique can for

10   example be used, wherein the energy encountered in the seismic data along a curve that corresponds here to the multi-offset traveltimes calculated by ray tracing is summed. In an ideal case, there will be a velocity sample for which the predicted traveltime curve is perfectly superposed on the seismic event considered, which will translate into a maximum coherence measurement. It can be noted that this evaluation can be

15   performed on a limited offset range, defined by the user or automatically, for example by examining the curve showing the evolution of the coherence as a function of the offset range.

For each multi-offset collection, the traveltime curve which best matches the seismic records is selected, and the multi-offset traveltimes forming this curve are

20   reserved. It can be noted that the traveltime curve exhibiting the best coherence can be adjusted if necessary by seeking in a predetermined vertical window the closest amplitude maximum (or minimum, depending on the polarity of the event considered) for each seismic trace of the multi-offset collection considered.

I-6 The multi-offset traveltimes thus collected for all the multi-offset collections selected are then injected into a prestack kinematic inversion method such as a traveltime tomography in order to determine the geometry and the velocity of the layer in question.

5   I-7 One may have to iterate the previous stages if the coherence with the seismic records is not considered to be globally satisfactory by the operator.

II - Particular cases

II-1 In cases where the velocity distribution in the layers of the geologic formation is greatly variable laterally and/or where no sufficiently precise a priori on the velocity

10   distribution in the layer considered is available, the method according to the invention comprises the following stages :

The previous stages are applied iteratively, the traveltimes collected during an iteration being used for updating the velocity model by means of a prestack kinematic inversion method such as traveltime tomography, a model which is then used as the

15   input velocity model for a new iteration of the method.

It can be noted that, in order to be free from the effects of the lateral velocity variations that might have a smaller wavelength than the maximum offset of the multi-offset collections, the offset range considered by the method can be widened as the iterations progress. More precisely, the method is initiated on a limited offset range,

20   then the velocity distribution found from this limited offset range is used as the reference model for a new iteration of the method during which a wider offset range will be considered, and so forth. It can be noted that the offset range considered at a given iteration can be selected for example by examining the curve showing the evolution of the coherence as a function of the offset range.

For the cases where the velocity distribution varies greatly laterally, it is possible to adopt furthermore a multi-grid approach, more precisely, the method is initiated on a loose grid of multi-offset collections (in order to determine the great wavelengths of the velocity variations), then multi-offset collection grids that are increasingly finer as
5   iterations progress are taken into account.

II-2 In the case where the sought interface geometry generates triplications and if it is also desired to determine the zones of the layer considered generating these triplications, it is first and foremost necessary to have inversion methods such as (fixed-velocity and prestack) kinematic inversion methods for example, allowing to take
10   account of multi-valuated arrivals. Such a method is described in the following reference :

- Delprat-Jannaud, F. and Lailly, P., (1995), How to handle multiple arrivals ? Journal of Geophysical Research, 100, No.B1, 703-715.

The input data of this type of method are the multi-valuated traveltimes associated
15   with the seismic events considered, and the ray parameters associated with these traveltimes. In order to obtain the multi-valuated traveltimes and the ray parameters associated with the constant-offset data, a migration-demigration loop can be used (as described in the aforementioned method by Ehinger and Lailly (1995)) by carrying out the demigration stage by means of ray tracing allowing to calculate multi-valuated
20   arrivals. Such ray tracing is for example described in :

- Jurado, F., Lailly, P., and Ehinger, A., (1998), Fast 3D two-point raytracing for traveltime tomography : Proceedings of SPIE, Mathematical Methods in Geophysical Imaging V, 3453, 70-81.

Then, after forming the various interface/velocity pairs by kinematic inversion at fixed velocity on the time/ray parameters data thus obtained, the kinematic information is calculated as described in the most general case by means, for example, of multi-offset ray tracing in each one of these models and for each multi-offset collection

5   selected, but this time adapted to the multi-valuated arrival calculations as described in the aforementioned document by Jurado et al. (1998). Both prestack multi-valuated traveltimes and their associated ray parameters are thus obtained for each multi-offset collection selected.

Then, the coherence analysis between the traveltime curves thus predicted and the

10   events considered in the seismic data is carried out as described in the most general case, but independently for each branch of the multi-valuated arrivals. The traveltimes thus collected for each branch of the multi-valuated arrivals are then injected, with their associated ray parameters, in a prestack kinematic inversion method allowing to take account of the multi-valuated arrivals, as described in the aforementioned document by

15   Delprat-Jannaud and Lailly (1995).

We have described here an application of the method to determination of a velocity model of seismic waves in an underground formation. It is however obvious that the method can also apply to determination of the velocity of propagation of other types of waves in a heterogeneous model exhibiting discontinuities.